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14. ABSTRACT
Earthen embankments include levees and dams provide water supplies, protect from flooding events, and provide significant environmental services. These embankments are of concern to agencies responsible for their construction, maintenance, inspection, and failure mitigation. Many of the techniques to assess and monitor dams and levees require substantial preparation and effort. Due to the extent of the embankment system and the high cost of failure, rapid, low-cost, highly-reliable inspection and monitoring technologies are needed. A workshop was

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Workshop on Monitoring and Failure Detection in Earthen Embankments

ABSTRACT

Earthen embankments include levees and dams provide water supplies, protect from flooding events, and provide significant environmental services. These embankments are of concern to agencies responsible for their construction, maintenance, inspection, and failure mitigation. Many of the techniques to assess and monitor dams and levees require substantial preparation and effort. Due to the extent of the embankment system and the high cost of failure, rapid, low-cost, highly-reliable inspection and monitoring technologies are needed. A workshop was held at the US Army Corps of Engineers Waterways Experiment Station 9-12 February 2009 to explore the state-of-the-art in inspection and monitoring, to identify technologies that might be applied in the near term, and to define a roadmap for research investment. Common threads in the recommendations include the need to test technologies on well-characterized sections of levees or dams; the need for improved models; the need for a better understanding of the physical phenomena; the need for improved sensors, including sources and receivers, as well as data acquisition systems and signal processing algorithms; and the need for an improved cyberinfrastructure to facilitate the rapid dissemination of data and test results.

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1. USDA Earthen Embankment Dams: Defining the Problem, G. Hanson (USDA-ARS Stillwater)
2. ERDC Levee Concerns: Scope and Magnitude of the Problem, M.L. Pearson (US Army Engineer Research & Development Center)
3. Embankment Erosion Process Model Development, G. Hanson (USDA ARS, Stillwater)
4. Preferential Flow Through Soil Pipes Causing Internal Erosion and Ephemeral Gully Erosion, G. Wilson (USDA ARS, NSL)
5. Summary of Recent and Current Work on Underseepage and Piping Along Levees, E. Glynn (US Army Engineer Research & Development Center)
6. Reliability and Risk Associated with Levee Systems, R. Gilbert (Univ. of Texas, Austin)
7. Non-Intrusive Seismic Profiling of Earthen Embankments with Surface Waves, K. H. Stokoe (Univ. of Texas, Austin)
8. Interrogating Levees in Southern Texas, New Mexico, and New Orleans Using Various Seismic Methods, Julian Ivanov (Kansas Geological Survey)
9. Use of an Acoustic Technique to Detect More Permeable and Less Permeable Layers, Chung Song (Univ. of Mississippi)
10. A Multi-Channel Analysis of Surface Waves (MASW) Method for Levee and Dam Assessment, Zhiqu Lu (Univ. of Mississippi)
11. Seismic Refraction Tomography on Earthen Embankments, Craig Hickey (Univ. of Mississippi)
12. Time-lapse Electrical Geophysical Methods for Subsurface Characterization and Monitoring, R.J. Versteeg (Idaho National Labs)
13. Using Helicopter Electromagnetic Surveys to Identify Potential Hazards at Mine Waste Impoundments, R. Hammack (National Energy Technology Laboratory)
14. Use of Non-invasive Monitoring for Embankment Monitoring – A European/UK Prospective, J. Simms (H.R. Wallingford, Ltd, Oxfordshire, UK)
15. How to Experiment on a Levee-Preliminary Lessons Learned from the Ijkdijk Stability Test, A. Koeelewijn (Deltares Geo-Engineering, Delft, Netherlands)
16. Sensor Systems, Actuators Systems Containing Infrastructure and ICT of Large Scale Smart Levees, R. Meijer (TNO, Univ of Amsterdam, Netherlands)
17. Integrated Geophysical Surveying for the Safety Assessment of Levee Systems, Tomio Inazaki (Public Works Research Institute, Tsukuba, Japan)
18. Surface Geophysics on New Orleans Levees - Post Katrina, John Lane (US Geological Survey)
19. Geophysical Surveys for Assessing Levee Foundation Conditions, Jose Llopis (US Army Engineer Research & Development Center)
20. Improving Remote Characterization of the Subsurface by Integrating Geophysical and Hydrologic Models, S. Moysey (Clemson University)
21. Constitutive modeling of the non-linear response of soils with application to failure of Earthen Embankments, Tarabay Antoun (Lawrence Livermore National Laboratory)
22. Perspectives of nonlinear seismic wave application for failure detection in earthen embankments, Alexander Sutin (Stevens Institute of Technology)
23. Moisture Effects on Sound Speed, the Nonlinear Parameter, and Shear Strengths of Soil: Their Role in Dam and Levee Assessment, Zhiqu Lu (Univ. of Mississippi)

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WORKSHOP ON MONITORING AND FAILURE DETECTION IN EARTHEN EMBANKMENTS
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SUBMITTED TO:

US ARMY RESEARCH OFFICE

by

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15 JUNE 2010

Final and Technical Report

I. EXECUTIVE SUMMARY

Earthen embankments include levees and impoundment dams that are used to control water flow. These structures provide water through periods of drought or between rainfall events, buffer and protect people from flooding events, provide water to farmers to ensure the supply of food and fiber to the American public, and provide significant environmental services. These embankments are of concern to federal agencies responsible for their construction, maintenance, inspection, and failure mitigation and to the regional, state, and local communities responsible for their maintenance and that are protected by them. The cost of failed embankments in terms of injury, displaced persons, and economic impacts can be immense.

Many of the inspection techniques to assess and monitor dams and levees, other than visual inspection, require substantial preparation and effort. Due to the extent of the embankment system and the high cost of failure, rapid, low-cost, highly reliable inspection and monitoring technologies are needed. Based on this technology shortfall, a workshop was held at the US Army Corps of Engineers Waterways Experiment Station in Vicksburg, MS from 9-12 February 2009 to explore the state-of-the-art in earthen embankment inspection and monitoring research and practice, to identify technologies and methods that might be applied in the near term, and to define a roadmap for future research investment.

To achieve these objectives, experts in applicable fields were identified and brought together from government, industry, and academia. The meeting involved a variety of experts, including members of the Army Corps of Engineers, USDA, Department of Homeland Security, academia, and foreign nationals from Japan, Israel, the Netherlands, and the United Kingdom.

Active source technologies, including seismic, acoustic, electromagnetic, and electrical methods, have the potential to provide information about the onset of piping, seepage, and anomalous pore pressures prior to failure. These active methods can detect and image anomalous zones in physical properties within the subsurface because these properties control the velocity, attenuation, and impedance of the interrogating waves from the source. Of these active technologies, seismic methods, in particular, employ relatively short wavelengths and experience low attenuation, allowing them to sense to moderate depths while retaining good resolution.

Passive technologies, including acoustic, gravitational, magnetic, self potential, or thermal methods, can be positioned over long periods of time for change detection that might indicate the onset of failures.

Non-linear methods offer the possibility of detecting the presence of internal cracks and damage; degraded dams and levees may generate much higher variations in non-linear responses when compared with linear acoustic and seismic parameters.

Because earthen dams and levees display a high degree of heterogeneity, multi-sensor approaches appear to offer the best solution for assessment and monitoring. Multiple geophysical techniques can be employed because compromised zones will disrupt a group of physical properties in a unique way. For example, excessive seepage will have distinct signatures in several technologies. The diverse sensors measure disparate physical properties, reducing false alarms and increasing the probability of detection.

Common threads appear throughout the recommendations. These include the need to test technologies on well-characterized sections of levees or dams with known zones of weakness; the need for improved models to aid in the selection of appropriate methods and placing of sensors and to predict sensor performance; the need for a better understanding of the physical phenomena underlying soil erodibility, susceptibility to internal erosion, nonlinear effects, etc.;

the need for improved sensors, including sources and receivers, as well as data acquisition systems and signal processing algorithms; and the need for an improved cyberinfrastructure to facilitate the rapid dissemination of data and test results.

II. FORWARD

We would like to thank the organizing committee for their guidance on the selection of attendees, facilities, and the structure of the workshop. The US Army Corps of Engineers Waterways Experiment Station hosted the workshop and provided valuable tours of laboratories of interest to the workshop attendees and on-site support. This report is a compilation of the input from the breakout groups and the workshop attendees are thanked for their contributions. Dr. Zhiqu Lu led the writing of the non-linear acoustic section. Dr. Craig Hickey led the writing of the active, passive, and multiple sensing technologies of the report and served in the lead role in the overall preparation of this report; he is gratefully acknowledged.

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IV. INTRODUCTION

Earthen embankments include levees and impoundment dams and are used to control water flow. These embankments are of particular concern to federal agencies responsible for their construction, maintenance, inspection, and failure mitigation and to the regional, state and local communities that are responsible for their maintenance and that are protected by them. The cost of failed embankments in terms of injury, displaced persons, and economic impacts can be immense.

The extent of the embankment systems in the United States and overseas makes this an enormous, expensive, and time-consuming task. The US Army Corps of Engineers is responsible for the inspection of approximately 2000 levee systems spanning thousands of miles along US rivers. Nearly 11,000 flood control dams have been constructed by the United States Department of Agriculture nationwide in 2,000 watersheds since 1944. These watershed projects represent a $14,000,000,000 infrastructure, providing flood control, municipal water supply, recreation, and wildlife habitat enhancement. Some of these dams are exceeding or approaching their projected life expectancy of 50 years (Bennett, Rhoton, and Dunbar, 2005). The Department of Homeland Security is responsible for protection of critical infrastructure including dams and levees and provides emergency response in the event of failure.

The risks of dam and levee failure include threats to urban and/or residential areas. The levees maintained by the Corps of Engineers protect cities, towns, industrial areas and agricultural regions. While the earthen dams constructed by the US Department of Agriculture were primarily situated in rural areas, increasing urbanization and suburbanization has led to the incorporation of these reservoirs in parks and recreational areas. As noted above, many of these dams have exceeded their design life. Since these dams and levees are and will remain a part of the populated environment, their failure, whether from natural causes or terrorist activity, represents a substantial risk.

Many of the inspection techniques, other than visual inspection, require substantial preparation and effort. Due to the extent of the embankment system and the high cost of failure, rapid, low-cost, highly reliable inspection and monitoring technologies are needed. Based on this technology shortfall, the Army Research Office and the USDA Agricultural Research Service identified a need to develop effective methods to inspect and monitor earthen embankments such as levees and dams.

A workshop was held at the US Army Corps of Engineers Waterways Experiment Station in Vicksburg, MS from 9-12 February 2009 to explore the state-of-the-art in earthen embankment inspection and monitoring research and practice, to identify technologies and methods that might be applied in the near term, and to define a roadmap for future research investment. This roadmap identifies long-term objectives, promising technologies, key participants, necessary resources, and a course of action to meet the long-term objectives. To achieve these objectives, experts in applicable fields were identified and brought together from government, industry, and academia.

The success of the workshop rested upon selection of the right participants. An organizing committee composed of Government experts and program managers was empanelled to recommend the selection of participants. In addition the workshop was advertised at the 12th Annual Landmine & Buried Explosive Object Detection Research Review. Organizing committee members included:

Organizing Committee

- Russell Harmon *(U.S. Army Research Office)*
- Mike Shannon *(U.S. Department of Agriculture Agricultural Research Service)*
- Mary Ellen Hynes *(Department of Homeland Security)*
- Paul Mlakar *(US Army Corps of Engineers)*
- James Sabatier *(University of Mississippi)*
- Craig Hickey *(University of Mississippi)*

The meeting involved a variety of experts, including members of the US Army Corps of Engineers, USDA, Department of Homeland Security, academia, and foreign nationals from Japan, Israel, the Netherlands, and the United Kingdom.

Total Attendees 35

United States	30	85.7%
Netherlands	2	5.7%
Japan	1	2.9%
Israel	1	2.9%
United Kingdom	1	2.9%

Department of Defense	8	22.9%
Other Government	9	25.7%
Academic	15	42.9%
Industry	3	8.6%

Table 1. Workshop attendee statistics

Experts in select topical areas were solicited to make keynote briefings to stimulate discussions. Breakout groups were created to facilitate small group discussions. In addition, several briefings were presented by "user" experts who have worked in dam and levee assessment, to provide "real-world" experience to the workshop.

There were three breakout sessions for each group. The objective of the first session was to summarize the current state-of-the-art for their technology area. The second identified barriers or limitations for that technology area. The goal of the third session was to describe a way forward, a plan of action to identify and achieve near and long-term objectives. Following each breakout session, the group leaders summarized the results of the session for the entire workshop assemblage.

V. TECHNOLOGY REPORTS

The failures of levees and earthen dams are associated with erosion of the surfaces, slope failures and slides, and seepage or piping through the foundations or bodies of the levees or dams. A concise description of the characteristics, causes, and preventive measures of the various types of failures can be found at http://environment.gov.ab.ca/info/library/6209.pdf.

The standard procedure for assessing the integrity of an earthen dam and levee includes several steps. The first step is visual inspection. The visual inspection involves looking for indications of excessive seepage through the embankment or through the foundation material under the dam, or seepage along the interfaces between the embankment and dissimilar materials like the conduit through the dam or the undisturbed material at the abutments. If visual evidence exists, then further inspection, including borings, installation of piezometers to measure pore water pressures, or other instrumentation to detect permeable strata will be required (McGregor, 2007).

Two overview presentations defining the problems on earthen dams and levees were presented at the beginning of the workshop to establish the scope and nature of the effort required to assess the integrity of earthen embankments within the United States:

- USDA Earthen Embankment Dams: Defining the Problem, G. Hanson *(USDA-ARS Stillwater)*
- ERDC Levee Concerns: Scope and Magnitude of the Problem, M.L. Pearson *(US Army Engineer Research & Development Center)*

Additional technical presentations highlighted the physical processes associated with internal erosion within earthen embankments and soils:

- Embankment Erosion Process Model Development, G. Hanson (*USDA ARS, Stillwater)*
- Preferential Flow Through Soil Pipes Causing Internal Erosion and Ephemeral Gully Erosion, G. Wilson *(USDA ARS, NSL)*

Two presentations illustrated the geo-statistical methods for prediction of locations of levee failure and evaluation of risk:

- Summary of Recent and Current Work on Underseepage and Piping Along Levees, E. Glynn *(US Army Engineer Research & Development Center)*
- Reliability and Risk Associated with Levee Systems, R. Gilbert *(Univ. of Texas, Austin)*

A. Active Technologies

1. Overview

There are numerous geophysical methods consisting of mature technology that are widely used to image and characterize subsurface geology. Many of these technologies can be adapted to the interrogation and characterization of earthen embankments. Geophysical methods are classified as active when some form of known, controlled energy source is used. Common active seismic

techniques include reflection, refraction, surface wave, and borehole techniques. Acoustic methods refer to methods using the compressional seismic wave and/or methods which use airborne acoustic sources such as loudspeakers. Active electromagnetic methods are developed using both frequency domain and time domain signal acquisition. Included in these are induction methods as well as the well-known ground penetration radar method. Electrical methods, such as electrical resistivity tomography and induced polarization, are also considered active methods.

A detailed exposition of geophysical exploration methods can be found in Telford, Geldhart and Sheriff (1998). Brosten, Llopis, and Kelly (2005) present an overview of geophysical methods used to assess the condition of small embankment dams.

2. Technical Presentations

The following presentations included information on active technologies:

- Non-Intrusive Seismic Profiling of Earthen Embankments with Surface Waves, K. H. Stokoe *(Univ. of Texas, Austin)*
- Interrogating Levees in Southern Texas, New Mexico, and New Orleans Using Various Seismic Methods, Julian Ivanov *(Kansas Geological Survey)*
- Use of an Acoustic Technique to Detect More Permeable and Less Permeable Layers, Chung Song (*Univ. of Mississippi)*
- A Multi-Channel Analysis of Surface Waves (MASW) Method for Levee and Dam Assessment, Zhiqu Lu *(Univ. of Mississippi)*
- Seismic Refraction Tomography on Earthen Embankments, Craig Hickey *(Univ. of Mississippi)*
- Time-lapse Electrical Geophysical Methods for Subsurface Characterization and Monitoring, R.J. Versteeg *(Idaho National Labs)*
- Using Helicopter Electromagnetic Surveys to Identify Potential Hazards at Mine Waste Impoundments, R. Hammack *(National Energy Technology Laboratory)*

2.1 Advantages

Subsurface seismic imaging can provide unique, valuable information regarding the integrity of an earthen dam or levee. The seismic method has the potential to provide the precursory information about the onset of piping, seepage, and anomalous pore pressures before actual failures occur. Active seismic methods are currently being tested for imaging of earthen dams and levees (Miller and Ivanov, 2005; Ivanov *et al.*, 2005; Miller *et al.*, 2007; Hickey *et al.*, 2008).

The most common form of shallow seismic surveying records signals from a surface source into a line of equally-spaced geophones along the crest of the dam or levee to produce a cross-section of the subsurface. This produces a good balance between acquisition speed, processing ease, interpretation convenience, and anomaly characterization. The resulting cross-section appears to be less ambiguous and more easily interpreted than other methods.

The common active seismic techniques discussed here are reflection, refraction, and surface wave techniques. These methods can be further subdivided depending upon the wave type (shear wave, Rayleigh wave, Love wave, or compressional wave) that the user wants to selectively examine. The surface Rayleigh wave technique appears to be the most commonly used method for levee interrogation. The primary advantage of the surface wave technique is its tolerance to ambient seismic noise. However, seismic data can be information-dense. For example, the data from a three-component survey can be processed for compressional and shear wave reflection and refraction, as well as Rayleigh surface wave analysis.

All active seismic methods detect and image anomalous zones in mechanical properties and densities within the subsurface because these properties control the velocity, attenuation, and impedance of the seismic waves. For example, the measured speed of propagation of a seismic wave is directly related to a mechanical property of the material. It is the initial slope of the stress-strain curve; as such it is not a direct measure of material strength, but can be correlated to material strength.

The ability to detect a zone of weakness within a dam or levee does not only depend on the mechanical property contrast, but also on the size of the zone of weakness with respect to the seismic wavelength. Due to relatively short wavelengths and low attenuation, the seismic reflection method is capable of better target resolution than any other active technique and can sense to moderate depths.

Earthen dams and levees have many structural differences. Both dams and levees have spatially-varying properties that can lead to false predictions when looking at single surveys from individual techniques. Many levees have been upgraded over time and may be more structurally heterogeneous than dams. Multiple surveys at different times using the same technique, i.e. time lapse seismic surveying, can be employed to measure the change in physical properties associated with a compromised zone.

Levees are comparable in size to medium-height earth dams, but differ somewhat in their hydraulic function. Levees are primarily used to divert flowing water such as a river, whereas dams are used as a barrier to hold water within a reservoir. The hydraulic stress and scour due to the flowing water may compromise levees at a faster rate than earth dams. Predicting the evolution of levee and dam failures associated with scouring and overtopping requires a measure of surface erodability. The acoustic impedance of the ground surface has been studied with respect to its influence on the propagation of outdoor sound. Acoustic-to-seismic transfer phenomena have been used successfully to detect landmines. Theses acoustic methods could be modified to remotely and more rapidly measure surface properties of dams and levees that correlate with erodability.

2.2 Disadvantages

From a field deployment standpoint, active seismic techniques are labor intensive. Although the data is information-dense, surveys require relatively long deployment times. At the current time, the data must be post-processed to maximize its imaging capability.

Although the mechanical properties within a zone of weakness may be substantially different than the surrounding embankment, the size of the zone might be relatively small compared to the spatial sampling and averaging from typical seismic surveys. The seismic resolution is proportional to the wavelength of the interrogating wave. Source excitation and material attenuation control the higher-frequency measurements and, therefore, the resolution. This is a primary physics limitation on detection in small, compromised layers that seismic surveys and new acquisition methods seek to overcome. It is unlikely that seismic methods will be useful for detection of structures like animal burrows.

3.0 Near-Term Application and Technology Opportunities

The seismic methods, in particular the active seismic techniques, have a long history in shallow exploration (tens to hundreds of meters) for geology, environmental, and civil engineering applications. Near-term applications and technology opportunities exist in adapting and further developing this technology for assessing the integrity earthen levees and dams. These include the following:

- Existing systems should be tested on a well-characterized section of levee with known zones of weakness in the embankment and foundation.
- Simple numerical models should be developed that incorporate the shape of the dam/levee to predict the seismic behavior/seismic propagation, such as travel paths, and excitation behavior of the levee. These models would facilitate and assist in establishing field acquisition geometries.
- Non-traditional sensor configurations should be examined at the field scale. For example, sources could be placed on the levee/dam, within the reservoir, or down dewatering wells. Receivers could also be placed within these different areas as well.
- Several surveys should be carried out over one year with specific attention to the state of the levee/dam. For example a survey might be carried out during the dry summer season, during the wet fall and winter seasons, and during the high water spring season. Additional surveys could be carried out during specific events such as flooding events.
- Enhanced receiver technologies might include using MEMS technology, gimbaled geophones, and amphibious sensors for use on the upstream side of the dam.
- Acquisition speeds may be increased by enhancing streamer type arrays or other technologies.
- Surface acoustic measurements should be correlated to soil erodabilty.

There is significant room for improvements in seismic sources specialized for efficient operation at high-frequencies. It is essential to optimize both coupling and transmission efficiency of the source. This might be accomplished by developing new sources, or through the use of coded inputs such as maximum-length sequences, chirps, dynamic vibrator feedbacks, etc.

Near-surface seismic applications are affected by the strength, perhaps the non-linearity, the heterogeneity and anisotropy, and environmental changes on wave propagation through earthen embankment materials. These properties and changes can control the behavior and response of dams and levees and complicate the interpretation of the seismic data. Research is needed to better understand the geology, physical properties, and spatial variability (heterogeneity) of the host material.

4.0 Future Research Opportunities

Seismic methods have been widely utilized for imaging and characterizing the subsurface of the earth. A few studies have focused on imaging earthen dams and levees. Extended numerical, laboratory, and field research studies are needed for the specific application to earthen embankments. A database containing a compilation of the spatial and temporal variation of physical properties controlling the seismic signature, environmental influences, and scattering anomalies of both host materials and compromised zones is required for input into models.

Any active seismic system requires a mechanical source, ground vibration sensors, a data acquisition system, signal processing, and visualization. Research in this area must address the problems of developing a mobile, high resolution, active seismic imaging system.

Source Improvements: All active seismic methods would benefit from a multi-mode, codeable seismic source that provides effective target illumination at high frequencies. Currently, for some studies, results from seismic methods are limited by the effectiveness of the source. In addition, most active source acquisition experiments are limited by the speed and mobility of the source. Other considerations include:

- Shear wave sources, coupling efficiency, transmission efficiency
- High frequency sources, 250 Hz and above, low amplitude, high-frequency, Non-contact sources (e.g. airborne)
- Coded sources (e.g. M-sequences, chirps, etc.)
- Multiple modal source, compressional, shear, and surface wave excitation

Receiver Improvements: Desirable characteristics of a seismic receiver include the ability to be used in a mobile configuration. Research areas may include the use of geophones in land streamers, wireless capabilities that include analog-to-digital conversion at the sensor (i.e. in sensor processing). Other research possibilities include non-mechanical receivers, such as piezoelectric and fiber optic sensors, or non-contacting sensors such as laser, radar, and ultrasonic vibrometers.

Data Processing: Earthen embankment materials are highly-attenuating with many natural anomalies in mechanical properties. All granular materials behave as low-pass filters to the propagation of seismic waves. Research and development efforts must be targeted toward improving SNRs using both filtering and signal processing techniques.

Signal processing algorithms should be developed for fusion of seismic information with other technologies such as radar and EM. Platforms instrumented with other sensor technologies, such as radar, require specific strategies for integration to ensure that the same space is imaged. Full integration should be done such that all of the physical property models from each technique are incorporated into a ‘whole’ inversion. Software for automation and near real time data processing and visualization is a possible long-term research objective

One of the greatest differences between near and deep geophysical applications is the effect of strength, non-linearity, and heterogeneity and anisotropy, and environmental changes on wave

propagation through geomaterials. These properties control the mechanical behavior and seismic response of embankments and are a key element in properly interpreting seismic cross-sections. The particulate and frictional behavior of earthen embankment materials creates conditions that are unique. The increase of overburden controls the low-strain stiffness and wave velocity in soils. The increasing overburden creates a heterogeneous stress distribution that gradually changes the wave velocity with depth. Furthermore, the frictional behavior of soils prevents an isotropic stress distribution (i.e., the effective stresses are different in the vertical and horizontal directions). This anisotropy stress yields direction-dependent elastic wave velocity. Both the heterogeneity and anisotropy velocity distributions combine to create curved rays paths. The problem is further complicated when dams and levees have layers with different grain mineralogy, porosity and water content.

The effect of water saturation in embankments clearly cannot be disregarded. The presence of two phases (water and air) in the pore generates surface tension that increases the contact forces between soil particles. As the water saturation decreases, the water suction and the elastic wave velocity increase. That is, the elastic wave velocity increases during the dry season while it decreases after a rain fall. In the former case, the velocity distribution due to saturation effects increases towards the surface, while it tends to decrease towards the water table.

The complex stress distribution and degree of saturation in soils necessitates robust understanding of geomaterial behavior and proper models for elastic wave propagation. These models need to incorporate geomaterial information including soil classification and water content to properly evaluate distribution of information and interpretation of seismic data. For example, seismic migration techniques should consider both the gradual and sharp variation of wave velocities to avoid smearing migrated images of point reflectors.

Advanced numerical modeling of problems associated with levees should be carried out to: (1) assist the development of new sensors for rapid identification of structural weaknesses, (2) aid in the evaluation of new sensor methods for levee assessment, and (3) further widespread levee assessment, evaluation, and management that is computer-based and user-friendly. The computer modeling should include the geometry of the levee and its water basin and basement, as well as the geoacoustic parameters of its structures, either known *a priori*, or measured. Parameters for potential structural problem zones, such as the acoustic velocity of seepage layers, tubular vents, etc., can then input to the computer code, and can be varied in sensitivity studies pertinent to vulnerability and failure. Forward modeling would involve inputting known, measured or estimated parameters to predict a probable levee situation, while inverse modeling would involve inputting a suspected levee situation to determine a probable structural condition.

B. Passive Technologies

1. Overview

Passive technologies measure the ambient fields present at or near the earth's surface. These fields might be large, fairly-constant fields such the earth's magnetic or gravitation fields. Spatial anomalies and short term perturbations in these fields can be associated with local

changes in near-surface properties. Other passive technologies measure fields produced by local physical processes occurring in the subsurface.

Self potential (SP) methods have been used (e.g. Sheffer, 2005, Rizzo, *et al.,* 2004, and Revil, *et al.*, 2005) for characterization of seepage on dams and levees. In SP monitoring, data is collected by placing non polarizing electrodes along the dam, and collecting data for different combinations of electrodes. Forward modeling of the SP data is done by generating a predicted SP signal from forward hydrological models (e.g. Modflow) and by using an experimentally-derived coupling coefficient. Inverse SP codes can estimate head distribution through minimization of the observed vs. the predicted data

As part of the European IMPACT project, 6m high test embankments in Norway were tested for internal erosion with geophysical methods adapted (self-potential streaming, temperature sensing) to *monitor* changes.

Passive seismic methods listen to seismic signals produced by fluid-flow and mechanical failures within the embankments. Testing has also been carried out at the Hydraulic Engineering Research Unit in Stillwater, OK which used active and passive acoustic methods during internal erosion failure.

More common geotechnical instrumentation used for monitoring earthen embankments are described in US Army Corps of Engineers Manual No. 1110-2-1998, "Instrumentation of Embankment Dams and Levees". These include sensors to measure water content, pore water pressure, deformation, total stress, and temperature. This manual also discusses methods for measuring seepage emerging downstream and the passive seismic method.

2. Technical Presentations

The following presentations included information on passive technologies:

- Use of Non-invasive Monitoring for Embankment Monitoring – A European/UK Prospective, J. Simms *(H.R. Wallingford, Ltd, Oxfordshire, UK)*
- How to Experiment on a Levee-Preliminary Lessons Learned from the Ijkdijk Stability Test, A. Koeelewijn *(Deltares Geo-Engineering, Delft, Netherlands)*
- Sensor Systems, Actuators Systems Containing Infrastructure and ICT of Large Scale Smart Levees, R. Meijer *(TNO, Univ of Amsterdam, Netherlands)*

2.1 Advantages

A clear advantage of the passive techniques is they do not require active sources, only passive receivers. Passive COTS sensors have been developed for the real-time monitoring of petroleum reservoirs, mining activities, geothermal applications, and nuclear waste applications. Passive sensors are "persistent," in that they can be left in the ground and operated consistently for long periods of time. Linear sensor arrays can be constructed using multiple point sensors. One example of this technology is the use of fiber optic-based strain gauge arrays.

Currently electrical methods are not commonly used in a monitoring mode for levee characterization. While monitoring has been used in relatively small scale applications (1000-10000 m^2 sites), electrical methods have a significant potential of providing process information.

A large number of experimental facilities are available: one of the largest in the US is a tilting flume of 6'x30'x1.5'at the USDA NSL. Tests could also be conducted in the centrifuge at ERDC. Tests were carried out Wallingford, UK to examine breach processes, but none of these tests included geophysical testing. Work was also carried out at Delft prior to the Ijkdike tests to check appropriateness of full scale tests. Experience at Wallingford and at Delft suggests that these tests can be useful precursors to full-scale tests. A key issue for laboratory experiments is taking account of the scale of the material – not all scale effects can be taken into account.

Cyberinfrastructure allows for rapid dissemination of data to allow sharing to multiple end users. Such infrastructure will allow for more rapid communication between flood control centers allowing for enhanced decision-making support. Such an infrastructure would allow for archiving of data (historical records) and connecting to other sensor networks (e.g., GEOSS, CUAHSI Hydrologic Information System). The ability to share data would provide a stimulus for geophysical monitoring, modeling, development, and industry.

2.2 Disadvantages

Little work has been done on geophysical methods to identify the *susceptibility* of embankments to internal erosion (conductive layers, macro pores). A key challenge for geophysical investigators is to be able to detect the presence of small/thin initiation features associated with this failure mode .

Challenges for widespread use of electrical resistivity include the development of fieldable, low-cost systems, as well as a link between processes and properties of interest (e.g. moisture changes and change in clay properties resulting from moisture change) and the associated electrical signal. In addition, joint inversion of electrical and seismic properties (cf. the work by Meju *et al*., 1996), needs to be further developed.

Passive seismic methods listen to seismic signals produced by fluid-flow and mechanical failures within the embankments. However, there exist very little information on the seismic characteristics such as amplitude, spectral content, duration, and temporal evolution of mechanical failures with embankments. Attenuation is governed by the environment and can increase exponentially in the near surface. The attenuation can also vary substantially with weather conditions. Changes in attenuation will directly impact the useful range of this technique. Laboratory and field measurements of seismic emissions associated with fluid-flow through soils should be characterized.

While the understanding of the reasons for the initiation of slope instability are well known, little work has been done on the use of geophysical methods to detect and predict the *susceptibility* of embankments to this instability. The Ijkdijk tests have tested slope instability with internal instrumentation and surface LIDAR surveys.

The reasons for the initiation of erosion from overtopping are well known, recent work has been conducted to improve the understanding of the resistance offered by vegetative cover and describing head cut processes. Settlement/subsidence or lack of rising to take account of rising water levels or bed aggregation is a key issue and this includes local crest lowering due to human or animal activities. There is also an issue of fine fissuring of the surface which leads to susceptibility. No known work has been conducted on the use of geophysical methods to predict the *susceptibility* of embankments to this instability.

Development of cyberinfrastructure needs to be in parallel and not in front of key sensor networks for monitoring, geotechnical, and remote sensing technologies. At the present time we do not have the data to go into the cyberinfrastructure.

3.0 Near Term Application and Technology Opportunities

- Incorporate geophysical measurements as part of the observation suite during embankment failure tests.
- Conduct research on the use of geophysical technologies for the identification of cracks and slip surfaces. Investigate the use of acoustic/seismic methods for monitoring seismic emissions associated with the cracking/slipping.
- Investigate the use of remote sensing (LIDAR, D-Insar, laser scanning) for measuring geometrical changes in dams before slope failure.
- Develop remote sensing technologies using satellite imaging, aerial photography, and infrared mapping for detecting and delineating the degradation of vegetative cover.
- Obtain access to test sites with existing levees that can support multiple surveys or facilitate different groups with permission to share data.
- Collect, archive, and share “Perishable data” before and immediately after storms on levees. This will help establish the change in seismic characteristics near failure.
- Conduct field tests on levees with non-traditional acquisition schemes. Simple modeling would facilitate this.
- Conduct blind comparisons of data.
- Develop cyberinfrastructure for real-time (near-time) data collection from sensor networks, data structure / database development, common information space (distributed computing) / data portal, web based presentation & delivery system (sensor è database è internet).

4.0 Future Research Opportunities

- Obtain test sites having dams and levees built to known specifications and constructed so that they can be instrumented with sensors, such as buried geophones, tensiometers, TDR’s, etc.
- Develop urgent computing schemes to address real-time numerical modeling and forecasting
- Further signal analysis methods for advanced model-based interpretation schemes
- Develop virtual laboratories for real-time modeling and control feedbacks. Incorporate these laboratories into a training facility for dike operators (real-world simulators).
- Enhance the sensor telecommunication infrastructure (sensor telecommunication network & redundant networks).
- Incorporate home-based sensors linked to scientific monitoring networks

C. Multiple Sensor Technologies

1. Overview

Earthen dams and levees have many structural differences. Both dams and levees have spatially-varying properties that can lead to false predictions when looking at single surveys from individual techniques. Many levees have been upgraded over time and may be more structurally heterogeneous than dams. In order to deal with natural heterogeneity, multiple geophysical techniques can be employed since compromised zones will disrupt a group of physical properties in a unique way. For example, the formation of a zone of piping will produce a region of lower bulk density, lower seismic speeds, and higher water content.

Current geophysical techniques being utilized for investigating dams and levees include: acoustic/seismic, electromagnetic and resistivity, gravity, optical sensing, and radar . These techniques are sensitive to the distribution of the bulk "geophysical" properties (elasticity, electrical resistivity, dielectric constant, etc) in the subsurface that are in turn related to more "basic" properties (bulk density, water content, porosity, mineralogy, etc). Table 1 summarizes the geophysical techniques and some engineering applications. With the exception of magnetic, all the geophysical techniques may have application or limited application to the investigation of hydraulically active structures such as dams and levees.

Table 2. Geophysical techniques, physical properties, and engineering application

Geophysical Method	Physical property	Engineering Application
Seismic Refraction	Shear modulus, bulk modulus, bulk density	Depth to bedrock, material strength, permafrost, fracture and seepage detection, location of voids
Seismic Reflection	Shear modulus, bulk modulus, bulk density, acoustic impedance	Depth to bedrock, material strength, permafrost, fracture and seepage detection, location of voids
Seismic Surface Wave (MASW)	Shear modulus, bulk density	Depth to bedrock, material strength, permafrost, fracture and seepage detection, location of voids
Self potential (SP)	Streaming potential	Seepage detection,
Resistivity	Electrical conductivity	Seepage, depth to bedrock, location of voids, permafrost, metal detection
Induced potential (IP)	chargeability	Seepage, depth to bedrock
Electromagnetic	Electrical conductivity , magnetic susceptibility	Metal detection, seepage and fracture detection, permafrost
Ground radar (GPR)	Dielectric constant	Depth to bedrock, location of voids, seepage detection, permafrost
Gravity	Bulk density	Depth to bedrock, location of voids, geological structures
Magnetics	Magnetic susceptibility, metal content	Metal detection

2. Technical Presentations

The following presentations included information on multiple sensor technologies:

- Integrated Geophysical Surveying for the Safety Assessment of Levee Systems, Tomio Inazaki *(Public Works Research Institute, Tsukuba, Japan)*
- Surface Geophysics on New Orleans Levees - Post Katrina, John Lane *(US Geological Survey)*
- Geophysical Surveys for Assessing Levee Foundation Conditions, Jose Llopis *(US Army Engineer Research & Development Center)*
- Improving Remote Characterization of the Subsurface by Integrating Geophysical and Hydrologic Models, S. Moysey *(Clemson University)*

2.1 Advantages

Natural dams and levees have spatially-varying properties that can lead to false predictions of compromised zones. Geophysicists performing site characterization for geotechnical applications, mining exploration, and oil exploration employ several techniques in order to alleviate the ambiquity in geophysical interpretation. This approach could prove useful in reducing the number of false anomalies due to the heterogeneity of the surrounding native material and increase the confidence in the detection compromized zones.

Compromised zones, such as zones of excessive seepage, will have a distinct signature in several geophysical methods. For example, such a zone might be characterized by low sesimic velocity and low electrical resistivity. Each geophysical technique provides only one geophysical parameter, therefore to advance the reliability of safety assessments, several geophysical techniques must be combined to apply "joint inversion" procedures to obtain the final results.

2.2 Disadvantages

From a field deployment standpoint, active geophysical techniques are labor intensive**.** Collecting data using multiple geophysical techniques will be even more labor intensive. However, data for multiple techniques can be collected concurrently.

The absolute depth of anomalies from surface geophysical methods are not well constrained. These are usually constrained based on data from adjacent boreholes.

Joint inversion of multiple geophysical data sets is not well developed.

Geophysical signatures using multiple methods presented in the literature are case studies of natural occurring zones in dams and levees. The ground truth of the survey site is not very well known. The causes, temporal evolution of the zone of weakness, and degree of loss of integrity are not easily quantified.

3.0 Near Term Application and Technology Opportunities

- Further develop the relationships to convert geophysical properties to hydraulic and geotechnical properties, such as permeability.
- Further develop cross-plotting techniques, for example a cross-plot of resistivity and S-wave velocity obtained at the same time is quite useful to characterize both permeability and stiffness properties of the target levees.
- Incorporate geotechnical measurements with geophysical measurements. For example, grain size characteristics of materials are needed to convert electrical resistivity to permeability.
- Develop normalization schemes so that results from different geophysical methods can be overlaid to enhance qualitative interpretation.

4.0 Future Research Opportunities

- Develop inversion routines to quantitatively utilize data from different types of geophysical methods: for example, electrical resistivity and S-wave velocity
- Develop inversion routines based on a common geological or geotechnical models.
- Develop interferometric techniques that incorporate aspects of both passive and active methods. These techniques use background seismic “noise”, such as seismic vibrations created by automobile traffic, as the energy source for imaging the subsurface.
- Develop and test alternative geophysical methods that are based upon the coupling of physical phenomena: for example, the use of the seismo-electric method.

D. Non-Linear Methods

1. Overview

The nonlinear acoustic/seismic technique is a promising technology in geophysics, geo-engineering, and civil engineering, while the nonlinear acoustic methods have long been used in areas of medical imaging, non-destructive testing, underwater sonar, and landmine detection. The nonlinearity of earth materials is primary originated from the nonlinearity of the grain contacts. It is anticipated that the presence of internal cracks, damages, and degradation of levees and dams may generate much higher variation in nonlinear responses when compared with variations of linear seismic parameters such as seismic wave speed, seismic wave attenuation, and acoustic characteristic impedance. The origins and sensitivity of the nonlinearity of earthen infrastructures make it promising to develop a nonlinear seismic technique for integrity assessment and failure prediction for levees and dams.

2. Technical Presentations

The following presentations included information on non-linear behavior of earthen embankment materials:

- Constitutive modeling of the non-linear response of soils with application to failure of Earthen Embankments, Tarabay Antoun (*Lawrence Livermore National Laboratory)*

- Perspectives of nonlinear seismic wave application for failure detection in earthen embankments, Alexander Sutin *(Stevens Institute of Technology)*
- Moisture Effects on Sound Speed, the Nonlinear Parameter, and Shear Strengths of Soil: Their Role in Dam and Levee Assessment, Zhiqu Lu *(Univ. of Mississippi)*

2.1 Advantages

The nonlinear acoustic/seismic technique has long been used in areas of medical imaging for diagnosis of abnormal tissues and organs, in non-destructive testing for internal crack and damage detection and fatigue evaluation, in underwater acoustics for highly-directive profiling of sediments, and recently for landmine detection providing enhancement of imaging contrast and reduction of the rate of false alarms.

It is known that earth materials exhibit intense static and dynamic nonlinear behaviors, including strong acousto-elastic effects, dynamic wave hysteresis, and dynamic modulus softening. Although the physics underlying these nonlinear behaviors still remains unclear, there are many reasons to believe that a system based on measurements of nonlinear effects in seismic waves can be much more sensitive to the presence of internal cracks, damages, instability, and degradation of levees and dams than currently-used linear seismic methods.

The nonlinear effects may manifest in many ways: harmonic generation, nonlinear waves interaction (resulting in difference and sum frequency components), amplitude-dependent sound speed (resulting in resonant frequency and phase shifts), amplitude-dependent attenuation, and slow dynamics. Corresponding to these nonlinear phenomena, many techniques have been developed to determine the nonlinearity of materials and objects. The simplest nonlinear method is based on second harmonic measurements. The waves interaction method measures difference and sum frequency components. The frequency shift and phase shift methods measure resonant frequency and phase shifts at elevated sound levels. Among them, the waves interaction and the phase shift methods are most likely applicable to the assessment of levees and dams.

The waves interaction method uses two seismic sources (e.g. electromechanical shakers) operating at different frequencies. In the path of wave propagation, two waves interact with each other. Due to the nonlinear nature of earth materials, the wave interaction leads to the generation of difference and sum frequency components that are measured to extract the nonlinearity. The advantage of the method is that the resultant different and sum frequency components are mainly due to the nonlinearity of the medium, thus eliminating the nonlinear effects caused by the excitation sources. It is well known that powerful seismic vibrators generate their own high harmonics and an interface between a shaker and the ground may also create nonlinear responses due to contact nonlinearity.

The phase shift method is a recently-developed technique, which takes the advantage of one of the nonlinear properties, that seismic wave speed is amplitude-dependent. In this method, the small changes in wave speed induced by the increment of excitation level can be detected by a sensitive phase detection technique. Instead of measuring harmonics or combination of frequencies that are generally 40dB below the fundamental frequency component, the phase shift method measures the fundamental frequency, thus gaining much higher signal-to-noise ratio.

With the aid of a phase-locking technique, the detected signals could be thousands times lower in magnitude than that of noise. For this reason, the phase shift method is more suitable for field tests where ambient noise could be severely high and mask the received signals.

Another recent nonlinear seismic test with a powerful shaker is based on analysis of seismic wave variations between various sensors measured for varied levels of seismic wave excitation. This approach allows detection of all spectra of nonlinear effects and separation of nonlinear effects generated by sources from nonlinear effects in propagated seismic waves.

In general, the overall advantages of nonlinear acoustic techniques are based on the fact that nonlinear responses are sensitive to the presence of internal cracks, damages, instability, and degradation. Therefore the measured nonlinearity could be a good indicator reflecting the integrity of earthen infrastructures. Another advantage is their high sensitivity to the variations of internal structures.

2.2 Disadvantages

There is currently no practical application using nonlinear acoustic techniques for the study of levees and dams. The appropriate acoustic/seismic source, operating frequency range and intensity, setup configuration, and signal-processing algorithms have not yet been tested. There is lack of clear physical understanding of linear and nonlinear properties of earthen infrastructures and their variations due to the accumulation of cracks, damage, and degradation, as well as due to changing soil conditions and environmental effects.

In the waves interaction method, the signal levels generated due to nonlinear effects are much lower than linear techniques (usually the different frequency and sum frequency are 20 to 40 dB lower than the fundamental frequency), which limits the measurement range. In the phase shift method, elevated excitation levels may introduce contact nonlinearity, thus masking the intrinsic nonlinear properties of earthen embankments. One solution might be the use of hydro-acoustic sources submerged in the water reservoir.

It may be difficult to separate nonlinear responses from other effects such as changes in pressure, temperature, and water content. It may be also hard to compare the measurement from different locations in stratified and heterogeneous media. Nonlinear signals may also be generated from boundary conditions.

3.0 Near Term Application and Technology Opportunities

- Develop models describing soil linear and nonlinear properties and their changes due to damage accumulation. The models will predict correlation of nonlinear seismic parameters with internal flaws or potential failures. Modeling of nonlinear soil properties can be based on a granular model describing dependence of the soil nonlinear parameters on grain properties, internal pressures, and water content.
- Develop experimental laboratory systems for measurements of various types of nonlinear effects in soils including: harmonic and combination frequency generation, amplitude-dependent sound speed, amplitude-dependent attenuation, and the effects of slow dynamics.

- Through the above lab tests, improve physical understanding of soil linear and nonlinear properties and their variations due to the accumulation of cracks, damage, and degradation, as well as due to changing soil conditions and environmental effects
- Conduct methodology studies to determine methods, experimental configuration, and signal processing algorithms to measure nonlinear various nonlinear responses, including slow dynamics with commercially-available equipment used for seismic assessment of earth embankments.
- Conduct field measurements of various nonlinear responses of levees and dams including measurements of nonlinear responses in the process of failure.
- Develop methods for nonlinear effect measurements based on differential variation of signals between elements of the receiving array. Conduct field tests of seismic nonlinearity using currently-available equipment.

4.0 Future Research Opportunities

Previously-developed nonlinear seismic methods can detect variation of averaged nonlinear soil properties on the whole path of signal propagation or between two sensors. The novel methods of nonlinear seismic tomography can be developed and applied for levees and dams assessment. These methods can be based on interaction of continuous seismic waves with impulse waves initiated by powerful impacts or explosive sources. Another prospective method of nonlinear seismic tomography can be based on the focusing of seismic waves and measurements of nonlinear effects in the focal area.

- Develop nonlinear seismic tomography for imaging the levees and dams embankment
- Develop and test method of nonlinear seismic imaging based on focusing of seismic waves.
- Develop non-contact, rapid, mobile platform for screening levees and dams

VI. CONCLUSIONS

The workshop achieved its objectives of exploring the state-of-the-art in earthen embankment inspection and monitoring research and practice, identifying technologies and methods that might be applied in the near term, and defining a roadmap for future research investment.

Active technologies, including seismic, acoustic, electromagnetic, and electrical technologies, have the potential to provide precursory information about the onset of piping, seepage, and anomalous pore pressures before failures occur. These active methods can detect and image anomalous zones in mechanical properties and densities within the subsurface because these properties control the velocity, attenuation, and impedance of the interrogating waves from the source. Of these active technologies, seismic methods, in particular, employ relatively short wavelengths and experience low attenuation, allowing them to sense to moderate depths while retaining good resolution. On the other hand, active technologies are currently labor-intensive and require relatively long deployment times. Furthermore, the resolution is probably not sufficient to detect small structural defects such as animal burrows.

Passive technologies, including acoustic, gravitational, magnetic, self potential, or thermal methods, can be positioned over long periods of time for change detection that might indicate the onset of failures.

Non-linear methods offer the possibility of detecting the presence of internal cracks and damage; degraded dams and levees may generate much higher variations in non-linear responses when compared with linear acoustic and seismic parameters.

Because earthen dams and levees display a high degree of inheterogeneity, multi-sensor approaches appear to offer the best solution for assessment and monitoring. Multiple geophysical techniques can be employed because zones of erosion will disrupt a group of physical properties in a unique way. For example, excessive seepage will have distinct signatures in several technologies. The diverse sensors measure disparate physical properties, reducing false alarms and increasing the probability of detection.

Common threads appear throughout the recommendations. These include the need to test technologies on well-characterized sections of levees or dams with known zones of weakness; the need for improved models to aid in the selection of appropriate methods and placing of sensors and to predict sensor performance; the need for a better understanding of the physical phenomena underlying soil erodibility, susceptibility to internal erosion, non-linear effects, etc.; the need for improved sensors, including sources and receivers, as well as data acquisition systems and signal processing algorithms; and the need for an improved cyberinfrastructure to facilitate the rapid dissemination of data and test results.

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Advanced Concept Workshop on Failure Detection in Earthen Embankments
Agenda

9 February 2009 (Monday)

7:00 PM Workshop Introduction

Wine and hors d'oeuvres - Jefferson Davis Room, Battlefield Inn

History of Levees — Dr. Michael Namorato *(Univ. of Mississippi)*

USDA Earthen Embankment Dams, Defining the Problem — Gregory Hanson *(USDA Agricultural Research Service-Stillwater)*

10 February 2009 (Tuesday)

7:00 AM Registration

8:30 AM Introductions and Workshop Overview

8:30 AM Waterways Experiment Station Welcome — TBD

8:40 AM Charge to Participants — Russell Harmon & James Sabatier *(Army Research Office & Univ. of Mississippi)*

8:50 AM Presentations

8:50 AM ERDC Levee Concerns: Scope and Magnitude of the Problem — TBD *(US Army Engineer Research & Development Center)*

9:20 AM Integrated Geophysical Surveying for the Safety Assessment of Levee Systems — Tomio Inazaki *(Public Works Research Institute, Tsukuba, Japan)*

9:50AM Use of Non-Invasive Monitoring for Embankment Monitoring - a European/UK Perspective — Jonathan Simm *(H. R. Wallingford, Ltd, Oxfordshire, United Kingdom)*

10:20 AM Break

10:40 AM Non-Intrusive Seismic Profiling of Earthen Embankments with Surface Waves — K. H. Stokoe *(Univ of Texas, Austin)*

11:10 AM How To Experiment on a Levee - Preliminary Lessons Learned from the Ijkdijk Stability Test — Andre Koelewijn *(Deltares Geo-Engineering, Delft, Netherlands)*

11:40 PM Reliability of and Risk Associated with Levee Systems — Robert Gilbert (*Univ. of Texas, Austin)*

12:10 PM Lunch

1:10 PM Discussion Session 1

Topic: Define the state of the art

2:40 PM Break

3:00 PM Presentations

3:00 PM TBD — Roelof Jan Versteeg *(Idaho National Laboratory)*

3:15 PM TBD Stephen Moysey
(Clemson University)

3:30 PM Facility Tour
5:00 PM Break
7:00 PM Meeting of Report Writers and Contributors (Battlefield Inn)

11 February 2009 (Wednesday)

8:30 AM Presentations

8:30 AM Sensors Systems, Actuator Systems Containing Infrastructures and ICT of Large Scale Smart Levees Robert Meijer
(TNO, Univ of Amsterdam, Netherlands)

9:00 AM Embankment Erosion Process Model Development Gregory Hanson
(USDA Agricultural Research Service-Stillwater)

9:20 AM Summary of Recent and Current Work on Underseepage and Piping along Levees Eileen Glynn
(US Army Engineer Research & Development Center)

9:40 AM Interrogating Levees in Southern Texas, New Mexico, and New Orleans Using Various Seismic Methods Julian Ivanov
(Kansas Geological Survey)

10:00 AM Geophysical Surveys for Assessing Levee Underseepage Buck Chute Area, Eagle Lake, MS Jose Llopis
(US Army Engineer Research & Development Center)

10:20 AM Break

10:40 AM Use of an Acoustic Technique to Detect More Permeable and Less Permeable Layers Chung Song
(*Univ of Mississippi)*

11:00 AM Preferential Flow through Soil Pipes Causing Internal Erosion and Ephemeral Gully Erosion Glenn Wilson
(USDA ARS, National Sedimentation Laboratory)

11:20 AM Surface Geophysics on New Orleans Levees Post Katrina John Lane
(US Geological Survey)

11:40 AM TBD

12:00 PM Lunch

1:00 PM Presentations

1:00 PM Geophysical Surveys for Assessing Levee Foundation ConditionsJose Llopis
(US Army Engineer Research & Development Center)

1:15 PM Using Helicopter Electromagnetic Surveys to Identify Potential Hazards at Mine Waste Impoundments Richard Hammack
(National Energy Technology Laboratory)

1:30 PM A Multi-Channel Analysis Surface Waves (MASW) Method for Levee and Dam Assessment Zhiqu Lu
(Univ of Mississippi)

1:45 PM Seismic Refraction Tomography on Earthen Embankments Craig Hickey
(Univ. of Mississippi)

2:00 PM **Discussion Session 2**
Topic: Define barriers and obstacles
4:00 PM **Adjourn**
6:30 PM **Dinner - Jefferson Davis Room (Battlefield Inn)**
8:00 PM **Meeting of Report Writers and Contributors (Battlefield Inn)**

12 February 2009 (Thursday)

8:30 AM **Presentations**

8:30 AM Constitutive modeling of the non-linear response of soils with application to failure of Earthen Embankments — Tarabay Antoun (*Lawrence Livermore National Laboratory)*

9:00 AM Perspectives of nonlinear seismic wave application for failure detection in earthen embankments — Alexander Sutin *(Stevens Institute of Technology)*

9:30 AM Nonlinear Soil Materials — Murray Korman *(US Naval Academy)*

9:45 AM Moisture Effects on Sound Speed, the Nonlinear Parameter, and Shear Strengths of Soil: Their Role in Dam and Levee Assessment — Zhiqu Lu *(Univ of Mississippi)*

10:00 AM **Break**
10:30 AM **Discussion Session 3**
Topic: Describe the way forward
12:00 PM **Lunch**
1:00 PM **Prepare workshop report**
3:00 PM **Adjourn**

Appendix B

2009 Levee Workshop
Attendees

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